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## Perspective

# Wastewater treatment in 2050: Challenges ahead and future vision in a European context

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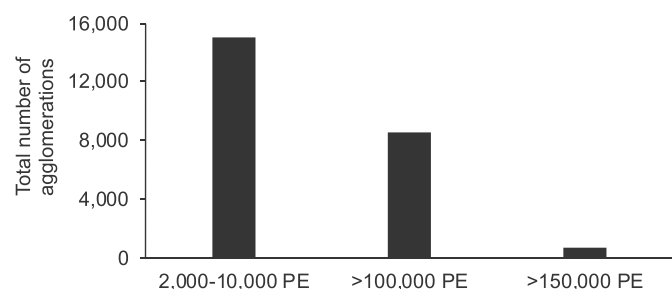
## 1. Introduction

The current state of the wastewater industry is one of transition. In Europe, in the last 2 decades, we have seen a significant improvement on river water quality after implementation of the Urban Waste Water Treatment European Directive (91/271/EEC [1], and the European Water Framework Directive [2]. Up to 97% of the population have now access to safely managed wastewater treatment services. The beginning of the energy crisis in 2006, coincided with the building and commissioning of large activated sludge plants, resulting in ever increasing electricity bills to be paid by municipalities and the wastewater industry. The upsurge in operational costs resulted in a wide questioning around WWTPs sustainability, the appropriateness of activated sludge to treat wastewater, especially when combined with the implementation of ever stringent regulations on effluent discharges, requiring total nitrogen and phosphorus removal, pushing process engineering and operational costs to critical levels. This led to a paradigm shift, around 2009, where “wastewater treatment” facilities were being proposed as the new “resource recovery and water recycling centres”. These ideas were not necessarily new, but the timing was impeccable as many renowned experts in the area, from industry, academia and consultancy, pushed for similar concepts, giving

origin to a wide acceptance of these ideas. Researchers, wastewater treatment service providers, and related industries took this opportunity with both hands, cemented by funding from national and international research councils, to develop a wide range of technologies that could deliver high effluent qualities with reduced energy demand, lower capital costs and operational costs, whilst achieving some sort of resource recovery. From biogas, to a very wide range of recovered products (e.g.: struvite, bioplastics, syngas, heavy metals etc etc) all sort of technologies have been developed at different technology readiness levels (TRL). Breakthroughs in technology development often originate at university level. There are a small number of elite universities highly geared up to secure funding, whilst collaborating with industry to fast track technology development. Nevertheless, globalisation and uniformization of processes for securing funding is also leading to the standardisation of experimental design, uniform rigging in labs, conducive to research results to align all over the world. Thinking outside the box is often not welcomed or understood by peers. Considering the time, effort and costs associated with developing new technologies, it is crucial to accurately quantify benefits prior to deciding further investment. Research and innovation by consultancies and large water services companies, often follow trends set by the academic community, but have a pivotal role fulfilling gaps by supplying suitable cost models and experience quantifying benefits. Furthermore, consultancies and large water services companies can move quickly on the ground, driving implementation. On the other side, most tend to be risk adverse placing high price tags on risk management. Platforms that enable tight collaboration in multi-disciplinary teams that can deliver accurate business cases, gather investment, whilst considering regulatory and social frameworks, to develop and demonstrate technologies that are considered high risk, is key for the future. We have started to see the materialisation of such collaborative platforms, but we need more to move forward.

In Europe, opportunities to develop greenfield sites are very scarce, and hence there is much focus on how innovative technologies could be integrated in existing WWTPs. Currently, the wastewater industry is faced with an absolutely staggering choice of technologies, many asking where to invest, develop, implement and why. These questions conveyed a wide range of modelling and decision support tools. Although these can give some sense of direction, the data sets utilised are often deficient, and the tools too

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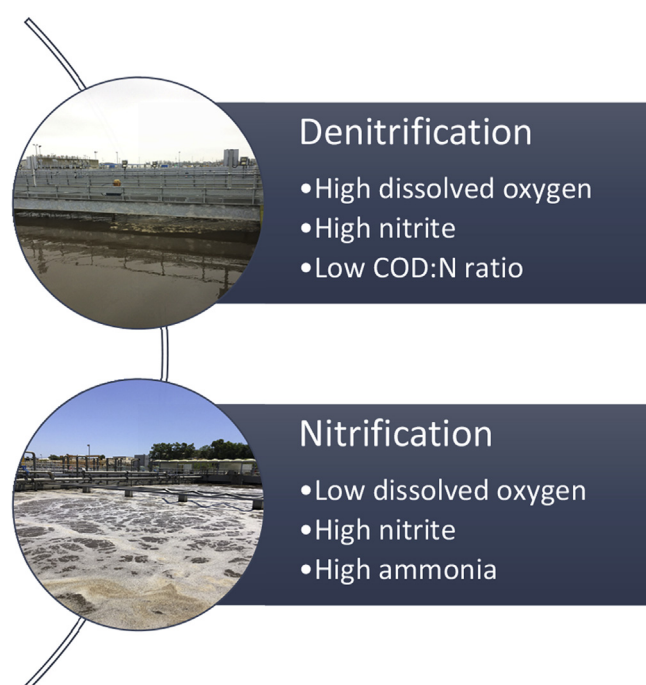
**Fig. 1.** Total number of agglomerations per population equivalent in the 28 European Union countries.

complex to grant a wide spread of users. On the other hand, there is a slow realisation that the scenarios in which WWTPs' integrate, is different for singular countries, communities, and regions. A design or flowsheet that fits all, has elapsed as we now realise that WWTPs in the south Spain to north Scotland need to be thought, designed, and operated differently to reach sustainability, integration with costumers, align with local vision and goals, and incorporation with the surrounding natural environment.

## 2. Wastewater treatment in 2030, the decade of intensification

A major barrier to implementing new technologies is the longevity of existing assets! Most WWTPs are decades old but still deliver a satisfactory service, so replacing or upgrading them entails a challenging and complex business case, many opting for doing nothing or just adding incremental processes. By 2030, the concept of primary, secondary and tertiary wastewater treatment is still very much in place. The latest technology developments will focus on process intensification, resource recovery and engineering systems to allow even higher effluent quality, attending to NET ZERO targets, i.e., achieving carbon emission neutrality. Some novel technologies that I believe are future proof and worth mentioning for their potential, include the combination of preliminary and primary treatment, like the Cellvation process. This recovers cellulose from wastewater, decreasing organic load to secondary processes, with the added benefit that the recovered cellulose can be used in the manufacture of wide a range of composite materials [3]. The biogas production from anaerobic digestion in WWTPs with Cellvation process is reduced, but this is not necessarily a negative, if articulated as a carbon capture process. Nereda® is another example of an intensified novel processes with reduced foot-print and capital costs. Nereda® aims at total nitrogen and phosphorus removal in sequencing batch reactors, achieving high effluent quality without the need of secondary clarifiers, relying on the high concentration of granular biomass to treat high loading rates [4]. Aerobic granular sludge is rich in polymers that can be extracted for a range of applications, including seed coating to enhance germination success (<https://kaumera.com/>). Deammonification through partial nitrification and anammox has been a huge success, with many installations worldwide aiming at the treatment of sludge dewatering liquors, with proved benefits on the reduction of ammonia load to secondary treatment [5]. Due to these advantages, the expansion of deammonification is very likely to continue in the next decade.

Some countries are enforcing nutrient resource recovery, especially for phosphorus, the "disappearing nutrient" from sewage sludge ash and biosolids [6]. Europe's nutrient natural reserves are extremely low (including P, K, Mg, S), as these are mined and imported from countries with social and political unrest. Shortage of



**Fig. 2.** Operational parameters applied to denitrification and nitrification processes that can lead to  $N_2O$  emissions (adapted from Ref. [10]).

nutrient supplies in Europe, can lead to critical levels in agriculture productivity, food production, increases in chemical prices, etc. When discharged to the environment, nutrients are pollutants, severely impacting natural habitats. Although technological advances are occurring at a fast pace to provide opportunities for nutrient recovery (e.g.: crystallisation of struvite, recovery of phosphorus from ashes or biochar produced from sludge thermal processing, etc) there is still a significant challenge for making these processes sustainable and economically feasible as well as providing an end route and entrance to supply chains and markets.

Furthermore, over the next decade we will see the wider digitalisation of WWTPs. The digitalisation of the water industry is mainly taking place in drinking water applications (e.g.: early warning systems for contaminants, variable pressure control in distribution networks, leakage detection etc) [7]. Meaningful big data analysis and artificial intelligence will make big leaps on the short term, but the wider automation of WWTPs is hindered by insufficient investment, lack of adequate staff training and remotising sensing difficulties. Installation and maintenance of sensors in WWTPs is notoriously difficult, due to short longevity of sensors, the need for frequent maintenance (due to fouling, interferences etc) adverse environmental conditions and accessibility. Digital twins offer a number of advantages, but only large and well maned treatment plants are likely to benefit from developments in this area. The vast majority of WWTP in Europe are small, remote, treating agglomerations from 2000–10,000 population equivalent (62%) (Fig. 1) [9].

## 3. Wastewater treatment in 2050

The next generation of technologies will be hugely influenced by the need to reduce carbon emissions combined with rigorous regulations whilst promoting water re-use. These are, once again, not necessarily new drivers, but the difference is that, by 2050, we will be making significant progress that will lead to their widespread and full-scale implementation. Delivery of the circular

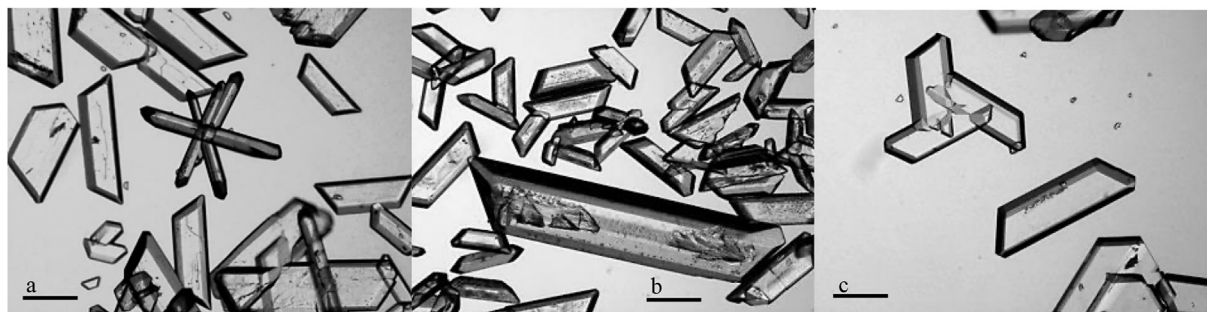


Fig. 3. Bio-struvite crystal produced by *B. pumilus* (a), *M. xanthus* (b) and *B. antiquum* (c) in municipal wastewater. Bar scale is 88.32  $\mu\text{m}$ .

economy will be a secondary driver, as the benefits to the wastewater industry together with uncertainty around public perception and regulation, have not been truly solved and demonstrated by 2020–2030.

We now can provide accurate and complete maps of direct and indirect greenhouse emissions. Carbon dioxide ( $\text{CO}_2$ ), is, of course a key gas, produced during biological oxidation of organic matter, burning of biogas and associated with the energy consumed in WWTPs. Methane ( $\text{CH}_4$ ) and nitrous oxide ( $\text{N}_2\text{O}$ ) are very relevant due to their global warming potential ( $\text{CH}_4 = 21.\text{CO}_2$  equivalent and  $\text{N}_2\text{O} = 310.\text{CO}_2$  equivalent). Methane emissions can originate from a wide range of processes, from primary sedimentation to denitrification tanks, but most importantly from sludge handling, reaching values up to 0.0085 kg  $\text{CH}_4/\text{kg}$  COD, hence managing these emissions is critical. Furthermore, there is an increased awareness that biological ammonia conversion to nitrogen gas is not sustainable, due to  $\text{N}_2\text{O}$  emissions and the energy requirement for aeration [11]. Nitrous oxide emissions vary greatly, but as much as 5% of the nitrogen load of a treatment plant can be emitted, depending on the operation of processes such as denitrification and nitrification (Fig. 2). Consequently, processes based on nitrification, denitrification, nitrification, deammonification and biological nutrient removal (with or without aerobic granular sludge) need to be rethought or upgraded. This is going to be one of the biggest changes in the next decades, nitrogen management. We will see the reduction of biological nitrogen removal based technologies as these will be replaced with alternative physical and chemical-based processes.

By 2050, transformative technologies will focus on gases production and recovery. Ammonia ( $\text{NH}_3$ ),  $\text{CH}_4$ , hydrogen ( $\text{H}_2$ ) and  $\text{CO}_2$ , can be produced, with subsequent separation from wastewater, offering a safe route to obtain clean streams leading to renewable energy or chemical production. The organic carbon within wastewater can be transformed to biogas in anaerobic membrane reactors with 80%  $\text{CH}_4$  content, achieving high effluent quality suitable for water re-use [12]. These are reactors are completely sealed and the dissolved methane recovered, leading to low GHG emissions and high methane recovery. The anMBR effluents are rich in nutrients. Ammonia can be recovered as a gas, through stripping or concentrated in liquid streams after concentration in brines [13,14]. Hydrogen can be produced by biological fermentation, electrolysis etc. [15] and  $\text{CH}_4$  and  $\text{CO}_2$  can be used to produce a range of high value chemicals [8,16]. Novel biological processes will be developed to explore microbial diversity on its entirety to harness the true power of microbes. The ability of microorganisms for produce highly specific and functionalised materials will continue to evolve to produce chemicals in a biotechnology engineering arena. Biomaterials, such as struvite can be produced in wastewater by specific bacteria that can concentrate ions, leading to the precipitation of specific salts (Fig. 3) [17,18]. The ions and

elements that can be extracted from wastewater are virtually unlimited! The microbial production of carbonate biominerals can promote  $\text{CO}_2$  sequestration, decreasing GHG and the recovered products have various applications such as improving the durability of buildings (biological cement) and can be used in composite materials, nanomaterial production. etc. Other examples of the exploitation of biomineral forming microorganisms include the production biomaterials, oxides, metals and semiconductors, nanomaterials, protective coatings for biomolecules, and other smart materials with exciting and new properties [19,20].

Overall, the next 3 decades will lead into the development of the next generation of WWTPs as pressures on the wastewater industry are mounting, and “business as usual”, and small step changes are not going to be acceptable. The decades ahead are certainly going to be busy for the wastewater industry!

### Declaration of competing interest

The author declares no competing interests.

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